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Thermoformed electronic skins for conformal tactile sensor arrays

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Abstract— **Robots and prostheses are increasingly designed with curvilinear surfaces for functional, aesthetic, aerodynamic, and safety reasons. Electronic skins (e-skins) capable of sensing contact location and pressure across complex, non-developable surfaces are essential for empowering next-generation robots with tactile awareness. This will facilitate safe and natural human-machine interactions while enhancing object manipulation capabilities. Despite the evident advantages of conformal e-skins, current fabrication methods face significant challenges in realizing their full potential. In this paper, we introduce thermoforming as a technique to efficiently fabricate tactile sensitive e-skins that conform to curvilinear surfaces. The performance, repeatability and uniformity of the sensors are characterized in detail. We also present a custom calibration pipeline where accurate digital replicas of conformal e-skins are generated for use in simulations. Finally, we demonstrate the benefits of 3D e-skins in a tool manipulation task.**

I. INTRODUCTION

In recent years, the expectation for robots to work alongside humans in everyday environments has grown significantly [1]. These robots are anticipated to interact with people, operate appliances, and manipulate a wide variety of household objects. Smooth, curved exterior surfaces are a crucial design element for home robots to gain public acceptance and meet consumer expectations. Rounded surfaces are also frequently seen on robotic and prosthetic hands, as they are not only aesthetically pleasing but also play a functional role in the fine manipulation of objects. Curved surfaces enable good contact to be achieved from multiple directions, allowing objects held in-hand to be easily rolled and re-oriented.

However, working alongside humans in unstructured environments requires robots to have enhanced environmental awareness, especially the sense of touch, to ensure safety, facilitate natural human-robot interaction, and improve object manipulation capabilities [2], [3]. Tactile sensors, like most electronics, are best manufactured using printed circuit technology, which struggles to cover curvilinear surfaces that cannot be flattened onto a plane (non-developable). Existing solutions typically involve partitioning a large surface into several small developable surfaces that can accommodate printed circuits [4]–[6]. While this approach may work for surfaces with minimal curvature, it is ineffective for areas with sharper curves and creases.

Furthermore, establishing a communication network across all skin patches to collect tactile signals is necessary, and the production and maintenance of an e-skin with numerous patches can be both expensive and complex [7]. Consequently, there is a need for a more effective method of integrating tactile sensing capabilities into robots with curvilinear surfaces.

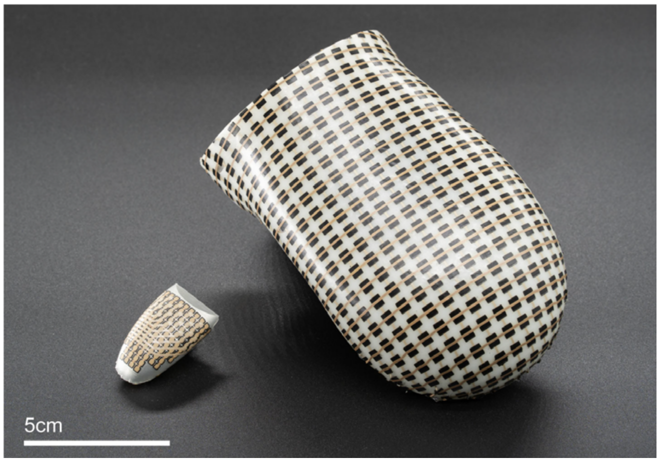

Fig. 1. Photograph of electronic skins conforming to a fingertip (left) and a curvilinear panel for a robotic arm (right).

An alternative approach involves producing tactile sensors on stretchable substrates [3], [8]. Despite intensive research in the field of stretchable electronics, there are limited methods for fabricating stretchable tactile sensor arrays at scale and in an economically viable manner. Furthermore, developing stretchable e-skins that are robust enough to withstand the rigours of an actual application remains a major challenge [7].

To address these concerns, we present a novel method for the fabrication of conformal electronic skins (e-skins). Our e-skin is fabricated on a flat substrate and subsequently shaped onto curvilinear surfaces by thermoforming. Once cooled, the e-skin is self-supporting and can be mounted onto external panels of the robot easily and repeatably (Fig. 1). Leveraging on established processes, our e-skin can be produced at scale using accessible equipment. Main contributions of this paper include:

- A novel technique for fabricating conformal tactile sensor arrays that can cover curvilinear surfaces is presented.
- A workflow to calibrate curvilinear tactile sensor arrays is established.
- The sensitivity, uniformity and repeatability of our conformal e-skin is reported.
- An exemplary application is showcased, highlighting the unique advantages of conformal e-skins for manipulation.

We begin with a survey of possible techniques for pro-

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ducing conformal e-skins, discussing the advantages and limitations of each approach (Section II). We then introduce our innovative fabrication technique, detailing the materials, processes, and design considerations involved at each step (Section III-A). As data-driven techniques become increasingly important for interpreting tactile signals, it is essential to develop accurate 3D models of tactile sensors, including their signal response to contact stimuli, for use in simulation environments. Consequently, this paper also describes a comprehensive procedure for calibrating and characterizing 3D e-skins (Section III-B). Section IV then presents experimental results demonstrating the performance and reliability of our e-skin and Section V concludes by summarizing the work and discussing the limitations of the current prototypes.

II. RELATED WORKS

The aspiration to make an entire robot's exterior touch-sensitive has been a long-standing goal for researchers [9]. Ohmura et al. introduced one of the first sensor systems capable of covering curved surfaces [4]. They developed flexible sensor sheets, each containing 32 sensing elements, which could be folded in two dimensions to conform to a curved surface. Although effective for a smaller number of elements, this technique would become labor-intensive when implementing thousands of elements, as required in a modern e-skin.

Later iterations of modular sensor patches, such as Hex-o-skin [6] and Robo-skin [5], were developed. Both approaches employ small patches of integrated electronics that network together to form a skin. Notably, Hex-o-skin incorporates a microcontroller on each patch, enabling more complex network architectures [10]. However, each Hex-o-skin patch consists of a rigid hexagonal PCB occupying $5.1\,\mathrm{cm}^2$, limiting its ability to form a smooth, continuous surface. In contrast, Robo-skin consists of triangular flexible PCBs, each with a data-acquisition chip that can be interfaced using an I2C bus. The flexibility of these patches allows for smoother surface coverage, but the limited bendability of the 4-layered flex PCB restricts Robo-skin's application to only modest curvatures.

Contact interactions across convex surfaces can be observed by monitoring surface deformations using embedded cameras [11]. Recent works have extended this concept to include sensing from an entire finger using multiple cameras [12]. However, the main drawbacks of this approach are the need for line-of-sight and sufficient distance between the camera and the surface to ensure good focus and illumination. This restricts vision-based tactile sensors to be used only at the fingertips if the robot is opaque, or in transparent soft robots.

Alternatively, electronic skins can be designed to be inherently stretchable [3]. Despite extensive research on stretchable electronics, developing elastic and durable interconnects compatible with existing components remains an ongoing challenge. Hua et al. [13] employed microlithography techniques to create ultra-fine meandering interconnects on a multi-modal e-skin, allowing up to 800% stretching while maintaining functionality. However, the skin is limited in size due to the constraints of lithography processes, while the large spaces required by the meandering patterns compromises the e-skin's spatial density. Wang et al. [14] fabricated an intrinsically stretchable e-skin using organic transistors with impressive results, although the device's longevity, a critical limitation of organic transistors, is not reported. Lee et al. [15] achieved highly stretchable circuitry by acoustically sintering liquid metal particles underwater, but the unique sintering process may not be compatible with the materials and structures required for tactile sensing. Stretchable e-skins without interconnects have also been attempted using Electrical Impedance Tomography (EIT) [8], but the complex computation and lack of spatial resolution in the middle of the skin remains a major challenge.

A promising new approach to creating conformable e-skins involves the use of knitted fabrics [16], [17]. By digitally knitting specially fabricated piezoresistive fibers with traditional yarns, tactile-sensitive garments such as gloves, socks, and vests can be produced. The resulting product can cover curvilinear surfaces and offers moderate stretchability, although the spatial resolution is reportedly limited by the minimum yarn thickness to 2 cm. However, due to the significant wriggle room of yarns within the matrix, these sensors are susceptible to motion artifacts and necessitate calibration procedures for individual sensors, which can be labor-intensive. Additionally, it remains unclear whether a re-calibration is necessary if the sensor's position shifts over time, such as when a sensor garment is removed and put back on.

Tactile sensor arrays can also be directly fabricated in 3D using advanced manufacturing techniques. In [18], the authors employ Laser Direct Structuring (LDS) to etch a 3D fingertip tactile sensor for a robotic hand. This method is only applicable to injection-molded parts made from specially treated plastic. Although LDS is well-suited for mass production, the tooling and equipment costs make it inaccessible for most research budgets. Alternatively, researchers have utilized multi-axis aerosol jet printing to create circuits on 3D surfaces [19]. A curvilinear surface would necessitate a printer with at least five axes of movement, while aerosol jets impose strict requirements on the compatible ink types. Such a specialized process may take time to become financially viable, especially for samples requiring larger work areas.

Recently, High Pressure Forming (HPF) has emerged as a process capable of achieving large-area free-form electronics [20]. HPF is a critical step in manufacturing touch-sensitive decorative panels commonly used in automotive and consumer electronics. Essentially, a sheet of thermoplastic polymer printed with decorative patterns and functional circuitry is heated to its glass-transition temperature and shaped into curvilinear forms using high pressure. A significant advantage of HPF is that the circuit is initially fabricated in 2D, making it compatible with conventional processes such as screen-printing, and subsequently transformed into 3D in a rapid and scalable manner. Recognizing the benefits of HPF, we aim to adapt this process for use in the production of

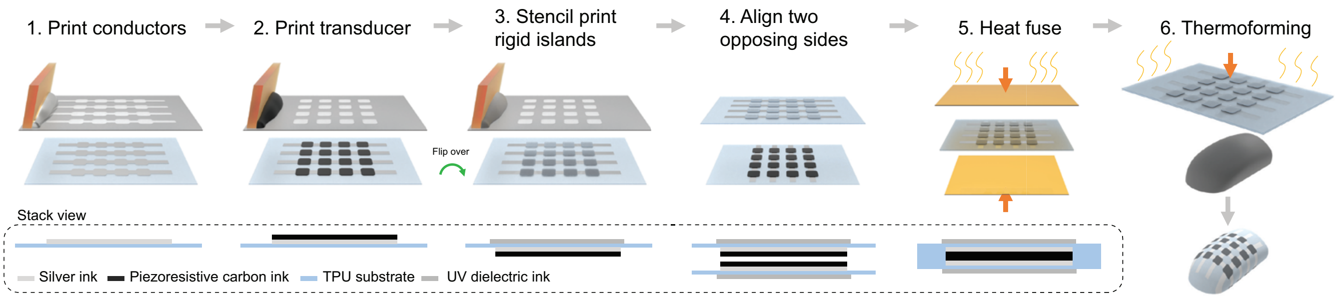


Fig. 2. Fabrication process of the curvilinear piezoresistive tactile sensitive e-skin. Printed ink was cured before the next process for steps 1−3.

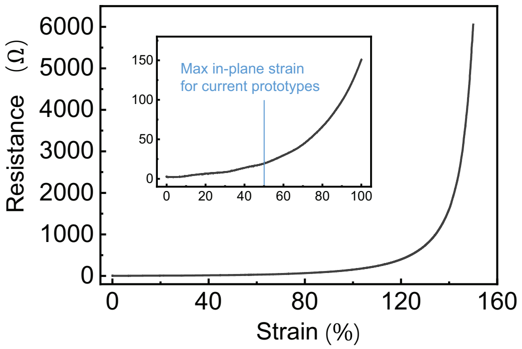


Fig. 3. Stretch-conductivity test of ASTMD-412-B dumbbell-shaped patterns of silver conductive ink printed on TPU. Inset shows an enlarged region between 0-100% strain for better clarity.

conformal tactile sensitive e-skins.

III. METHODS

A. Sensor fabrication

Our sensor essentially consists of an array of piezoresistive tactile sensing elements (taxels) arranged in a row-column order on a thermoplastic polyurethane (TPU) film. The fabrication of this array involves printing multiple layers of different materials in a specific sequence, with the actual process and design varying depending on application requirements. Fig. 2 illustrates the essential steps to fabricate a typical e-skin sheet.

Initially, the row electrodes are created by screen-printing stretchable conductive ink (SIP-2002, Dycotec, UK) onto a sheet of TPU (U073, Covestro, Germany) and curing it in an oven according to the manufacturer's specifications. Intersection areas with the column electrodes are coated with piezoresistive ink (CI-2050, Engineered Conductive Materials (ECM), USA) through screen-printing. The sheet is then flipped, and thin patches of UV-curable semi-rigid dielectric (DI-07-132, ECM, USA) are deposited onto areas corresponding to individual sensing elements via stencil printing. This enhances the rigidity of individual taxels, improving uniformity, repeatability and response/recovery time while reducing hysteresis.

The earlier steps are repeated on a separate TPU sheet for the column electrodes. Subsequently, the two sheets are sealed together using a heat press, ensuring alignment of the piezoresistive patches on the row and column electrodes. This process fuses the top and bottom sheets, forming a single e-skin sheet.

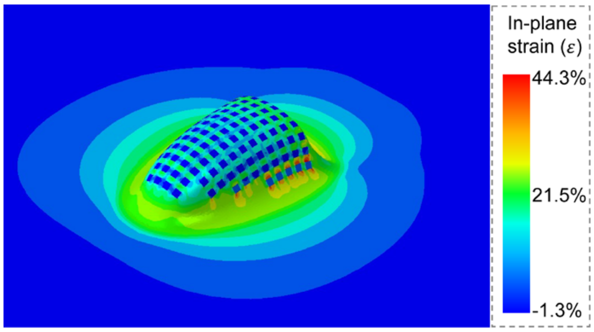
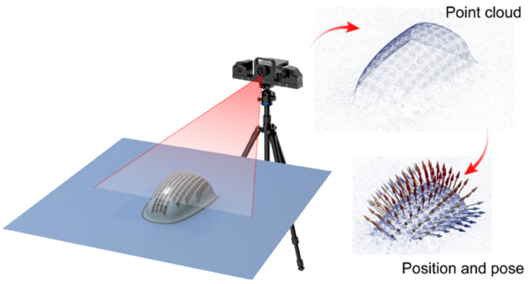


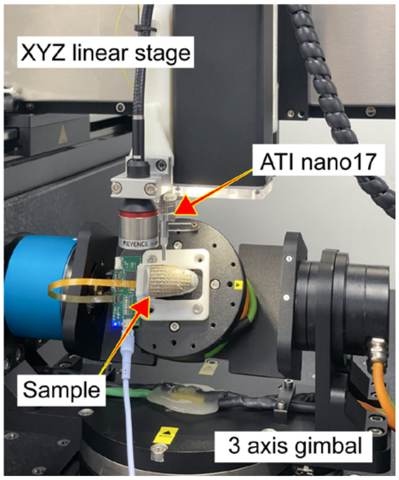
Fig. 4. Finite Element Model prediction of e-skin stretch during thermoforming.

To shape the sheet into a curvilinear surface, the e-skin undergoes a thermoforming procedure. First, the e-skin is uniformly heated to the glass transition temperature of the TPU (150°C), placed over a prepared mold, and vacuum is applied. Air pressure stretches and presses the sheet onto the mold and the sample is allowed to cool. Once cooled, a self-standing, curvilinear patch of e-skin is formed.

TPU substrates can be stretched up to 600% [21], theoretically enabling the e-skin to conform to a wide variety of arbitrary surfaces during thermoforming. However, the limiting factor is the stretchability of the conductive traces. Using ASTMD-412-B dumbbell-shaped specimens [22], we measured the resistance of the conductive ink when stretched. As shown in Fig. 3, a significant increase in resistance occurs when the ink is stretched beyond 100% (Fig. 3). This value is considerably lower than the stretchability of the substrate. Fig. 4 illustrates the amount of stretch an e-skin will undergo for a given shape, as predicted by our Finite Element Model. Current processes aim to keep the maximum strain below 50% for areas with conductive traces, ensuring that the trace resistance remains low enough not to affect the signal measurements. As new printable conductors with better stretchability become available, the versatility of our technique is expected to improve significantly.



(a) Pose and position of taxels are extracted from 3D scan using a custom script in Unity.



(b) Taxels are probed on a 6 axis stage using pose and position data from 3D scan.

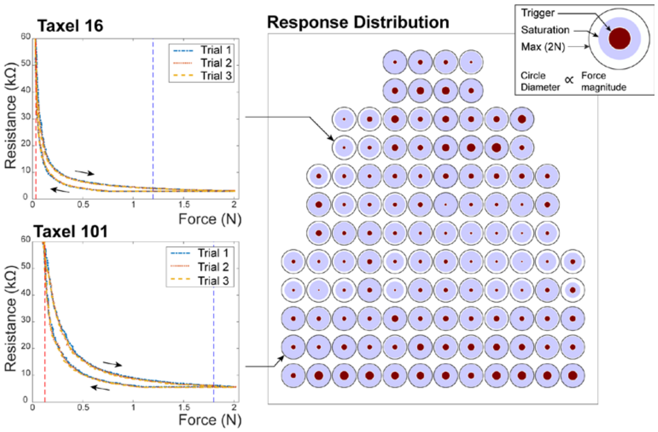
Fig. 5. Processes to calibrate a conformal e-skin

B. Calibration

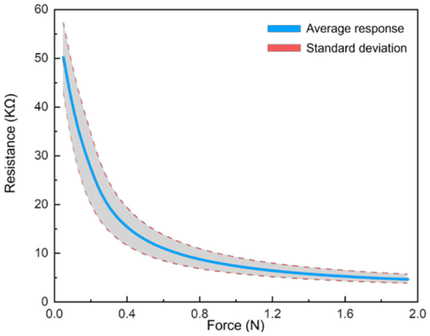
As robotics planning and control increasingly rely on simulations, it is crucial to have realistic models of tactile sensors for use in simulated environments. This is particularly important for conformal e-skins, as each taxel will have a unique pose and position. It is also beneficial to have a method for characterizing the transducer response of individual taxels after thermoforming for process optimization purposes.

Fig. 5 depicts the steps taken to calibrate a conformal e-skin. A 3D scanner (Transcan C, Shining3D, China) is employed to capture the shape and texture of the e-skin after it is mounted on the component. Using a custom script in Unity [23], the pose and position of each taxel are extracted from the scanned model. The extracted data is then utilized to build a Unified Robotics Description Format (URDF) for the e-skin (Fig. 5a).

A custom 6-axis test rig has been developed to perform automated transducer characterization of conformal e-skins (Fig. 5b). The rig comprises precision X, Y, and Z linear stages (Physik Instrumente, Germany) and a three-axis gimbal (Hengyuan Zhonglian, China). Using taxel pose information extracted from the 3D scan, the stage automatically probes individual taxels with a load cell (Nano17, ATI, USA). The toolhead of the rig is also equipped with a digital microscope and laser confocal distance sensor, which are used to evaluate the accuracy of the 3D pose data. In our observations, the positional error of taxels is typically below 0.2 mm.



(a) Mechanical characterization of fingertip e-skin. The force-response profiles of 2 selected taxels are shown on the left. Dashed vertical lines indicate trigger and saturation forces. The trigger and saturation forces of all taxels are illustrated on the right.



(b) Average respond trend for all 114 taxels during the loading phase. Shaded region corresponds to standard deviation.

Fig. 6. Load characterization of 114 taxels on fingertip e-skin

IV. RESULTS

The method described in this paper can be employed to create conformal tactile sensitive electronic skins of various sizes, shapes, and taxel densities. The performance (sensitivity, dynamic range, etc.) of the fabricated e-skins inevitably depends on multiple design factors. In this paper, we present results obtained for a conformal fingertip sensor optimized for a recent work [24]. The purpose of this section is to demonstrate that our technique can achieve conformal e-skins with good performance, but it is not intended to represent the highest performing metrics achievable.

The e-skin tested has 114 taxels distributed over a convex, elliptical surface. Each taxel measures 1.5×1.5 mm in size. Taxels in the array are spaced roughly 2.6 mm apart in both horizontal and vertical dimensions. The probe with a circular cross-section of 3 mm diameter was used, and the probe was indented perpendicularly onto each taxel. A total of three indentation trials were performed consecutively per taxel.

For brevity, a 2D visualization of the trigger force (defined as the minimum force needed to achieve a reading above 10% of baseline) and the saturation force (when response is below 1 KΩ/N) of all taxels are shown in Fig. 6a. Example

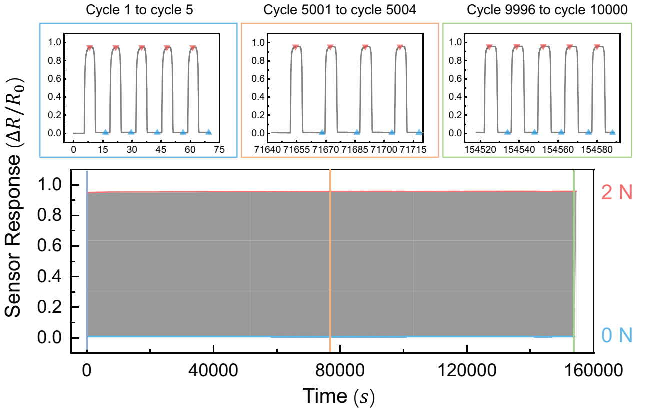


Fig. 7. Response to 10000 load/unload cycles. Insets represent magnified regions at cycles 1, 5001 and 9996 respectively.

responses from 2 typical taxels are also illustrated. The readout from the taxels are stable and repeatable across the trials. The average trigger force is computed to be 0.12±0.078 N. From the presented results, we can establish that all taxels in the e-skin respond to pressure with good signal-to-noise ratio. There is also no obvious correlation between the dynamic range of the taxel and its curvature after thermoforming, suggesting that the novel procedure does not degrade transducer performance significantly. Fig. 6b depicts the uniformity of the taxel responses during the loading phase. While some variation in sensor response is evident, further investigation would be required to determine the main cause of this phenomenon.

To investigate the robustness of the e-skin, we subjected a taxel to 10000 load cycles of 2 N force (889 kPa). Fig 7) depicts the response profile, where a mere 0.22% decrease in dynamic range is observed at the end of the test, suggesting that our thermoformed e-skins are robust to repeated use.

Convex fingertip surfaces offer several advantages in manipulation tasks. A rounded surface achieves good contact from various finger orientations, minimizing the need to reposition the fingertip based on the contacted surface. Additionally, objects can easily roll along the fingertip, allowing continuous tracking of the contact point throughout the motion trajectory [11]. This feature is particularly beneficial for in-hand manipulation tasks.

We demonstrate one such application in which a slender straw is manipulated in-hand by a three-fingered end effector to achieve a stirring trajectory. Using the URDF models of the fingertip e-skin generated from Section III-B, a control policy for the task is first obtained in simulation via deep reinforcement learning. The experimental platform includes a custom three-fingered gripper with 8 degrees of freedom. The fingertips were fitted with three conformal e-skins and wrapped in a soft silicone cover to improve compliance and grasp stability. When the policy is deployed on the physical platform, continuous feedback from the e-skins allowed the task to be accomplished without policy fine-tuning [24]. Fig. 8 illustrates how uninterrupted tracking of the contact location on all three fingers is maintained even as the slim object undergoes rotation along multiple axes, a behavior that would be difficult to replicate using flat fingertips or sensors. Readers are advised to refer to [24] for experimental details. The supplementary video on the task is provided, which also includes a collage summarizing the steps to fabricate and calibrate the prototypes described in this work.

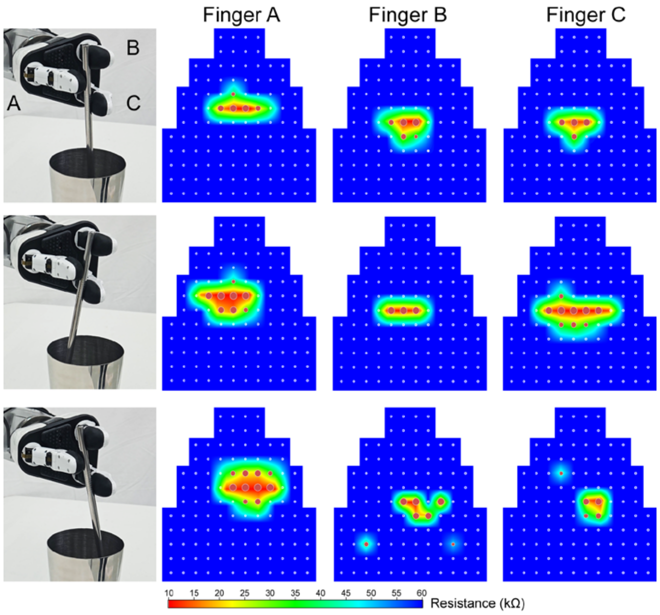


Fig. 8. Tactile signals at 3 time instances as a straw is manipulated in a stirring trajectory using only finger motion. Size of dots is proportional to sensed pressure magnitude, while the colored shading is a bi-cubic interpolation of resistance of all taxels.

V. CONCLUSION

In this paper, we introduced a novel method for fabricating conformal, curvilinear tactile-sensitive electronic skins. Leveraging established processes such as screen-printing and thermoforming, the e-skins can be manufactured in large pieces with high throughput. We also demonstrated how conformal e-skins can be calibrated and digital models generated for use in simulations. Characterization of a specific e-skin design is performed, showing good performance and uniformity of the taxel array after thermoforming, while the sensor maintains consistency even after numerous load cycles. Finally, we demonstrated an object manipulation task which utilized the simulated and physical e-skins to successfully perform a stirring action using a slender object, highlighting the advantages afforded by conformal tactile sensor arrays.

Several steps in our current production process, such as stencil-printing, pattern alignment, and thermoforming are currently performed manually. Consequently, significant and unavoidable sample variation will occur. As the techniques are further optimized using automated procedures, a detailed investigation of sample variation will be conducted. Larger and more complex e-skin shapes and patterns will also be explored in the future. We believe conformal e-skins will be an essential technology in the future of robotics, and our technique will play a significant role in enabling their proliferation.

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